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Role of the driver in the dynamics of a coupled-map model of the magnetotail: Does the magnetosphere act as a low-pass filter?

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Abstract. A coupled-map model of the magnetotail is used to study the dynamics of the magnetosphere. Using different types of colored noise as an input to the model, it is shown that the high-frequency part of the behavior is intrinsic to the model, while the low-frequency part reflects the dynamics of the input time series. It is also shown that the relation of the power spectra of the magnetospheric input (vB_S) and output (AE) time series is very similar to the relation of the power spectra of the model input and output. It is then argued that the magnetosphere acts, similarly to the model, as a low-pass filter. It is also suggested that the power law distributions of the AE data may be partly due to the power law distribution of polarity changes in the interplanetary magnetic field B_Z.

1. Introduction

The AE index, which describes the global activity of the auroral electrojet, has a "kink"-like (bicolored) power law power spectrum (PS), i.e., spectrum $\propto f^{-\alpha}$ with $\alpha \approx 1$ for low frequencies and $\alpha \approx 2$ for high frequencies, and a break point at about 5.6×10^{-5} Hz (1/(5hrs) [*Tsurutani et al.*, 1990; *Takalo et al.*, 1993]. Furthermore, *Takalo and Timonen* [1994] have shown that the break point is connected to the timescale of 2-2.5 hours which is the typical duration of auroral substorms. It should be noted that power law power spectra are characteristic of colored noise. Colored noise is self-affine such that there is no preferred scale in its dynamics.

It is interesting that AE time series also displays scale invariance in the duration and size of its disturbances; that is, the duration and size distributions of AE disturbances have power law forms [*Takalo*, 1993; *Consolini*, 1997; *Takalo et al.*, 1999b]. The duration was defined as the integral over a time with continuous nonzero integrand, $T = \int\theta(AE - C_{AE})\, dt$, where $\theta(\ )$ is the step function and C_{AE} ia a cutoff level of activity [*Takalo*, 1993; *Takalo et al.*, 1999b]. Using the data for the years 1979-1985 and C_{AE} = 100 nT, the power law slope of the duration distribution was -1.42 up to $\sim$ 100 min (see Figure 1). However, for durations longer than 100 min there is an excess of events over the power law extrapolation [*Freeman et al.*, 2000; *Takalo et al.*, 2000; *G. Consolini*, Avalanches, scaling and $1/f$ noise in the magnetospheric dynamics, submitted *to Physical Review Letters*, 1999], which is probably due to substorms.

It is still an open question whether these dynamic features in the AE index are an intrinsic property of the magnetosphere or induced by the solar wind / interplanetary magnetic field (IMF) input to the magnetosphere. It is a well-known fact that IMF also has a power law power spectrum. *Sari and Ness* [1969] found $\alpha \approx 2$ between 2.8×10^{-4} Hz $< f <$ 1.6×10^{-2} Hz for Pioneer 6 data, *Burlaga and Goldstein* [1984] found $\alpha \approx 5/3$ for 10^{-6} Hz $< f <$ 10^{-4} Hz between 4.1 and 5.2 AU for Voyager 2 data, and *Tsurutani et al.* [1990] found $\alpha \approx 1.4$ for IMP 8 B_Z component at frequencies 10^{-5} Hz $< f <$ 10^{-3} Hz. Recently, it has been shown that the burst-duration distribution of IMF vB_S [*Freeman et al.*, 2000] and the distribution of B_Z (also B_X and B_Y) polarity changes (change of sign) [*Takalo et al.,* 2000] have a power law form.

Spatial and temporal scale-free properties of the above type are characteristic of a phenomenon called self-organized criticality (SOC) [*Bak et al.*, 1988]. Furthermore, it has been suggested that the dynamics of the magnetosphere may be a consequence of SOC behavior and global coherence in the current sheet [*Chang*, 1992, 1998]. However, SOC is not the only phenomenon exhibiting scale invariance. Many classes of physical processes, e.g., systems near criticality, turbulence, transport in disordered systems, granular materials, may show scale invariance. As mentioned above it is also the basic property, e.g., of self-affine (colored) noise.

We show here that colored noise also has power law distributed polarity changes and suggest that the power law behavior of IMF may be caused by its resemblance of colored (fractal) noise [*Burlaga and Klein*, 1986]. Consequently, the power law behavior of the AE data may follow from the solar wind input to the magnetosphere [*Freeman et al.*, 2000]. We also suggest using a coupled-map lattice (CML) as a model of the magnetotail current sheet [*Takalo et al.*, 1999b] so that the high-frequency part of magnetospheric dynamics, as deduced from the AE index, is intrinsic to the magnetosphere while the low-frequency part may reflect the dynamics of the solar wind/IMF driver.

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2. Coupled-Map Model

The coupled-map ("sandpile") model has been introduced and described in detail in previous articles [*Takalo et al.*, 1999b,

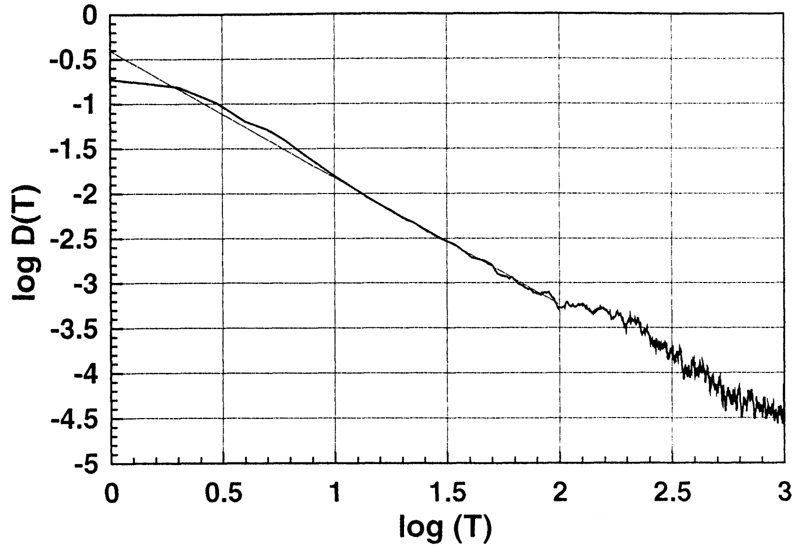

Figure 1. Duration distribution of magnetospheric disturbances as measured from the *AE* index of the years 1978-1985.

2000]. The model is two-dimensional with a 50×50 grid in the *xy* plane (Figure 2). The magnetic field is assumed to be in the z direction, representing the B_Z component of the magnetotail field in the equatorial plane at the current sheet. The instability threshold is set for the two-dimensional Laplacian. At every lattice cell where the Laplacian is greater than the critical Laplacian L_{cr}, the resistivity turns on, and is given by

$$\eta_{x,y} = \eta\theta\left(\left|L_{x,y}\right| - L_{cr}\right), \qquad (1)$$

where $\theta(\ )$ is the step function, $L_{x,y}$ is the Laplacian of the magnetic field at point (x,y), and $\eta = 0.25$ is used in this study. This resistivity actually represents the diffusion parameter in the model and brings the hysteresis needed for the long-lasting metastable states to produce nonlinear coherent behavior in the model. It should be mentioned that the instability is current-driven because the Laplacian is proportional to the line integral of the current density around the cell (flux tube) [*Takalo et al.*, 2000]. The evolution of the flux density can be expressed in the form

$$\frac{\partial B}{\partial t} = \frac{1}{\mu_0}\left[\frac{\partial}{\partial x}\left(\eta\frac{\partial B}{\partial x}\right) + \frac{\partial}{\partial y}\left(\eta\frac{\partial B}{\partial y}\right)\right] + S(x,y,t)\ , \qquad (2)$$

where $S(x,y,t)$ is the general (external) input term. The shape of

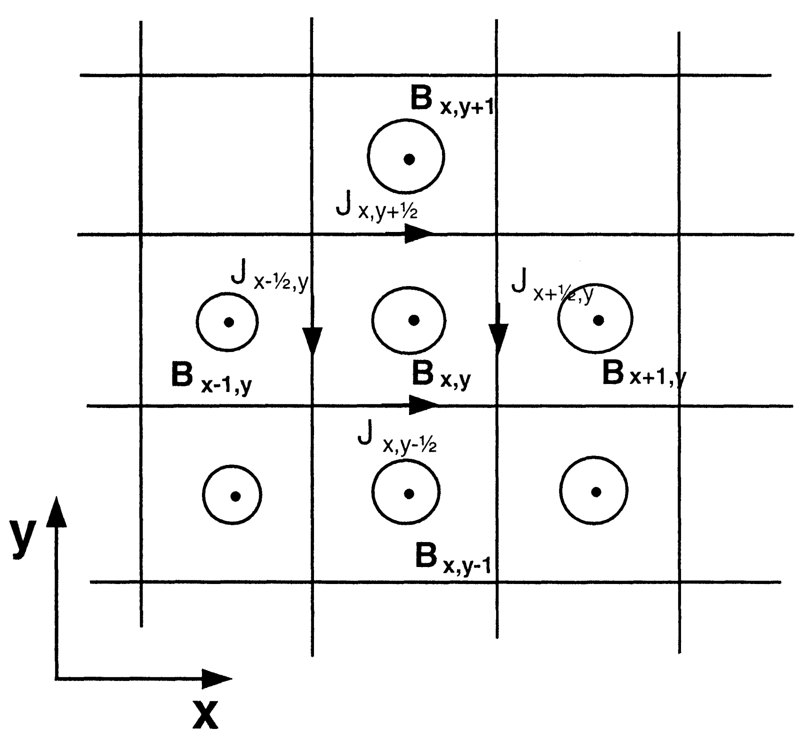

Figure 2. The cells of the coupled-map lattice each present one flux tube, here marked with $B_{x,y}$. The current between the flux tubes (x,y) and $(x+1,y)$ is marked with $J_{x+1/2,\ y}$, etc.

the model is shown in Figure 3a for $\eta = 0.25$ and $L_{cr} = 0.5$. After reaching a stationary state, perhaps a SOC configuration, the model fluctuates only around this shape. In Figure 3b we show a snapshot of these magnetic fluctuations. The field quantity (B_Z in Figure 3b) is continuous, and the model is a so-called "running sandpile" model [*Hwa and Kardar*, 1992] because it is fed by S at every iteration, not just in the state of relaxation, as in a "stop and go" model. The output time series of the model is in this study the number of unstable sites (cells where the resistivity is "on") at each iteration.

3. Input-Output Dynamics

In this study we are interested in to what extent the dynamics of the model is internal and to what extent it is caused by the input of the model. In this respect, we use different types of colored noise as the input signal. Only the other polarity is accepted as nonzero input (compare B_S); otherwise, only a small increment is provided in the input. This is similar to the case of solar wind vB_S where during northward polarity we use only small constant input. The noise sequences consist of N = 200,000 normalized data points calculated from the discrete Fourier series [*Osborne and Provenzale*, 1989; *Takalo et al.*, 1994]

$$X(j) = \sum_{k=1}^{N/2} C_k \cos(2\pi jk/N - \varphi_k) , \tag{3}$$

where φ_k are the random phases in the range $[0, 2\pi]$ and the coefficients C_k are related to the power spectrum $P(k) \propto k^{-\alpha}$ by $C_k = [P(k) 2\pi / N]^{1/2}$.

First, we drive the model with white noise ($\alpha = 0$) and record the number of unstable sites (the cells where resistivity is "on") in the model lattice grid at each step of iteration. In Figure 4a we show the power spectrum of the resulting output time series (bottom curve), and the PS of the input time series (top curve). It is evident that at high frequencies the internal dynamics of the model is displayed, while the power spectrum is almost flat at low frequencies. The slopes are -0.12 and -1.9 for the low and high frequencies, respectively. In Figure 4b the input time series is "pink" colored noise ($\alpha = 1$). The high-frequency part of the spectrum remains almost the same (slope is -2.0), but the low-frequency part now has the same slope, -1, as for the input. So it seems that the correlation in the driving time series penetrates the sandpile and appears also in the output time series. It has been stated before [*Takalo et al.*, 1999b, 2000] that the low frequencies demonstrate the correlations between separate

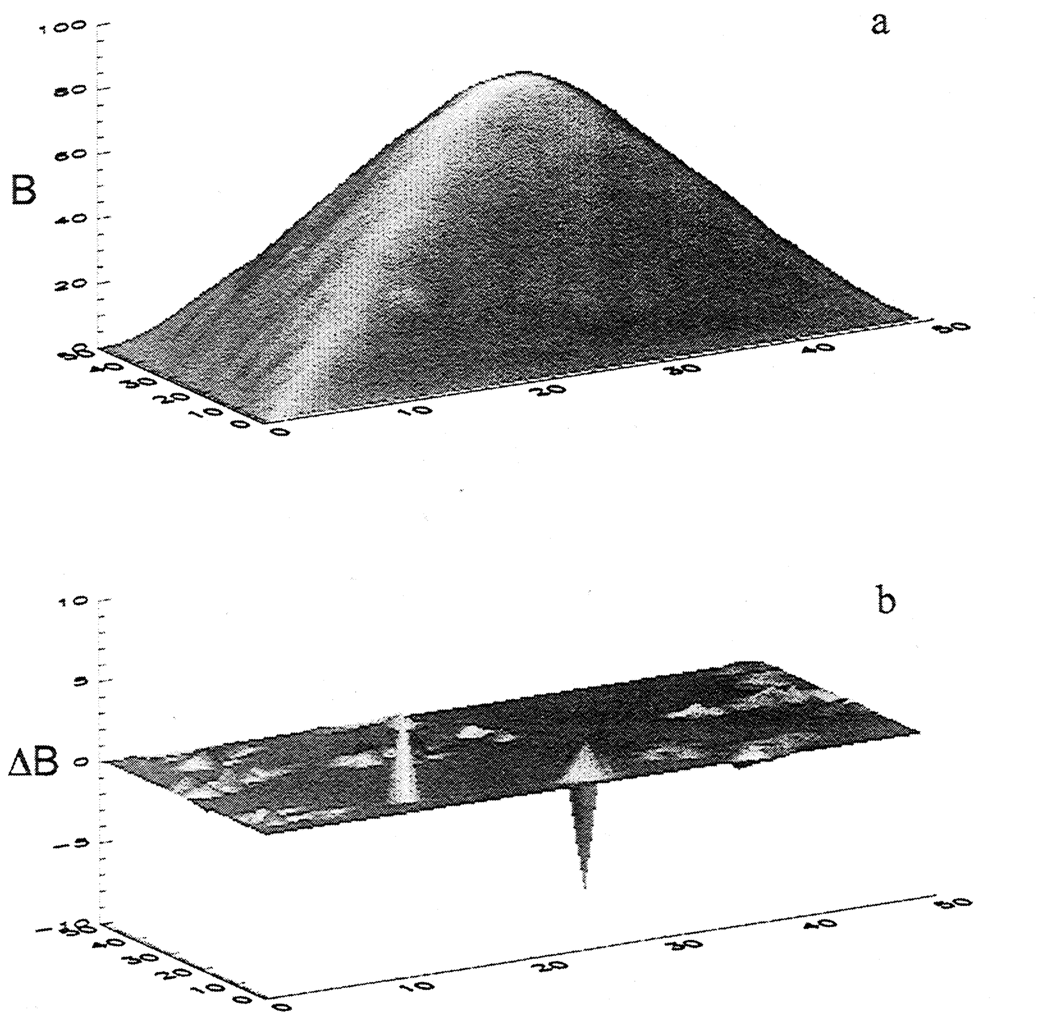

Figure 3. (a) Configuration of the magnetic field of the model in the long-term stable state. The height of the pile describes magnetic flux density B. (b) Instantaneous time derivative of the B between consecutive iterations.

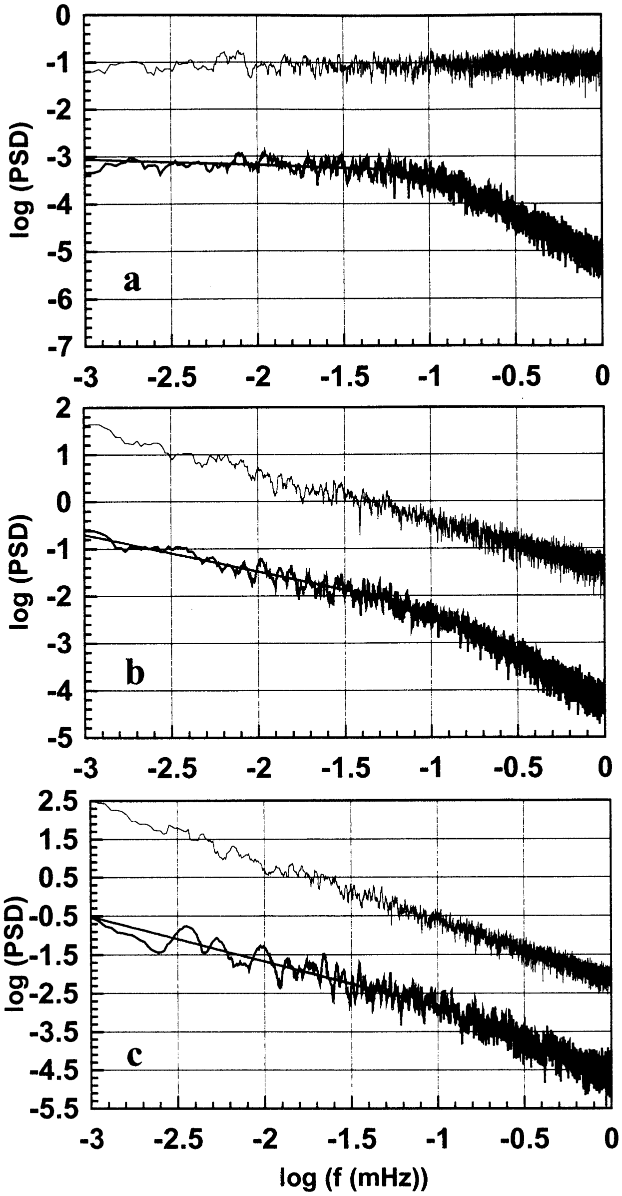

Figure 4. (a) The power spectra of the white noise (f^0, top curve) and the corresponding output of the model (bottom curve). (b) The power spectra of the f^{-1} noise (top curve) and the corresponding output of the model. (c) The power spectra of the $f^{-1.5}$ noise (top curve) and the corresponding output of the model.

avalanches in the model. This is true, but it seems that this correlation reflects also the correlation in the input data. Actually, *Takalo et al.* [1999b] have shown that the strength of the driver affects the slopes of both the high- and the low-frequency parts of the spectrum; however, it has greater affect on that in the low-frequency regime.

In the Figure 4c we plot the corresponding PS in the case of $\alpha = 1.5$ input. The high-frequency part is qualitatively the same (slope is -2.1) as in the previous cases. The low-frequency part (-1.2) seems to saturate near the slope -1 and is thus smaller in absolute value than that for the input data. Qualitatively, this means that the model weakens the correlation at low frequencies from what it was in the input time series. It should be noted that our model includes only diffusion and does not at present have a convection term in it. It may be that if convection were included it would reproduce the correlation better also at low frequencies. Also, the strength of the driver can affect the internal long-range correlations, and probably if the amplitude of the driver were larger, the slope of the low-frequency part of the spectrum would be a little steeper [*Takalo et al.,* 1999b, 2000].

In Figures 5a, 5b and 5c we show the time series of the colored noise α = 0, 1, and 1.5, respectively, with the

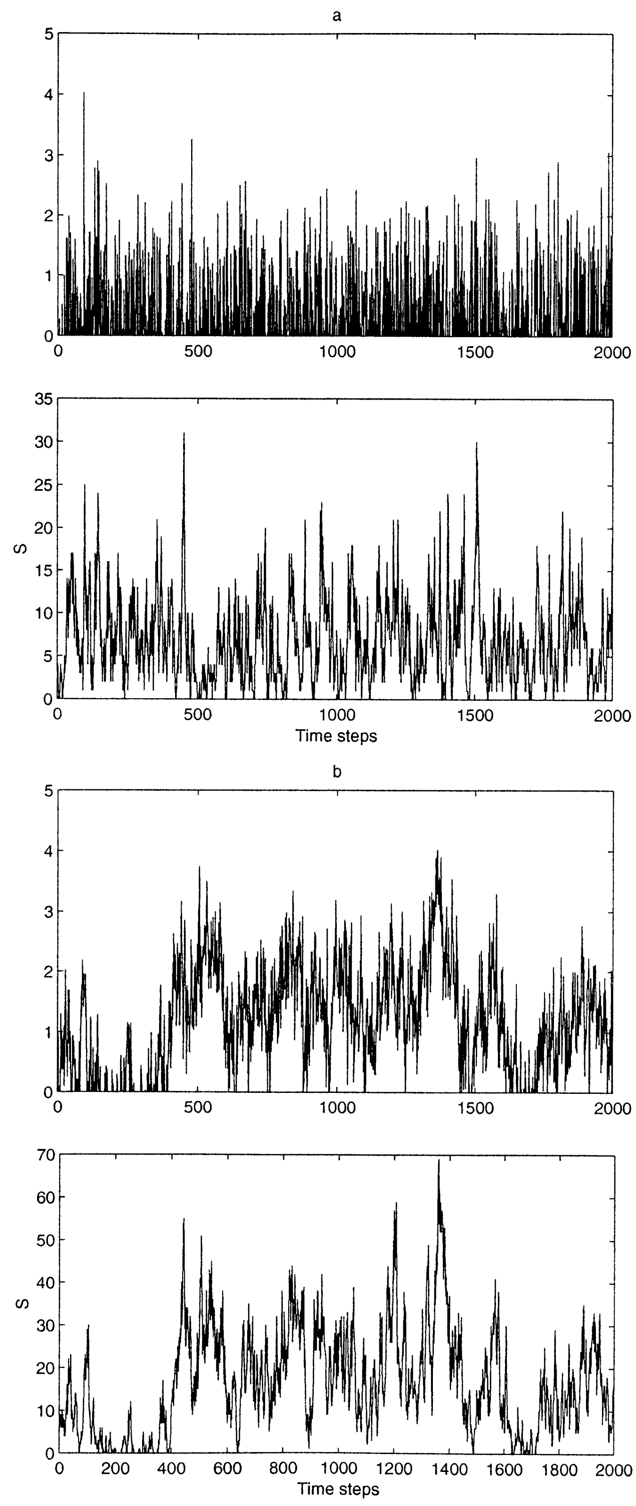

Figure 5. (a) Part of the time series of f^0 noise (top panel) and the corresponding output (bottom panel) as calculated as a number of unstable sites of the model. (b) Same as Figure 5a but for colored noise f^{-1}. (c) Same as Figure 5a but for colored noise $f^{-1.5}$.

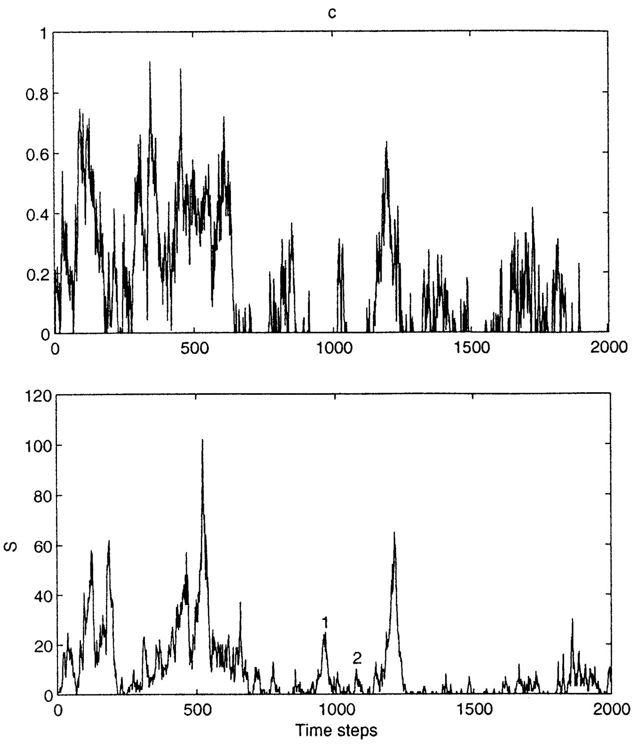

Figure 5. (continued)

corresponding output of the model. However, because of the resolution, we plot only part of these time series. Notice that at short timescales the output time series is smoother than the input time series. It should be mentioned that the maximum correlation between the input and output data is 0.13, 0.68, and 0.65 for 0, -1, and -1.5 noise, respectively. This also shows the saturation of the model behavior between the -1 and -1.5 input. Notice also that there are peaks, which are not triggered by the driver. In particular, the Figure 5c peaks marked by 1 and 2 do not have an instant external trigger, but the unloading is internal. This kind of behavior is typical for the model [*Takalo et al.,* 1999a] and is related in the intrinsic dynamics (the high-frequency part of the spectrum) of the model.

In Figure 6 we show the power spectra of the 5-min averaged vB_S (Figure 6a) and *AE* (Figure 6b) time series for 32,678 points of data starting from the beginning of 1979. The slopes for vB_S are -1.5 and −1.2 for the regimes log(*f*(mHz)) > -1.2 and −2.2 < log(*f*) < -1.2, respectively. There seems not to be any abrupt change in the slope, but the PS is bending smoothly during the long range of frequencies. The slopes are, however, similar to those found by *Tsurutani et al.* [1990], who reported values of −1.38 for B_S and −1.43 for B_Z using the data of 1978-1980. The PS of the *AE* time series has a characteristic bicolor form with a break point at the frequency of about 1 per 5 hours [*Tsurutani et al.*, 1990; *Takalo et al.*, 1993]. The high-frequency regime has a slope of −2.0, while the low-frequency part has a slope of −1.1. The high-frequency spectrum is evidently due to the dynamics inside the magnetosphere, but the low-frequency part is more similar to the corresponding part in the input vB_S power spectrum. Notice the similarity between Figure 6 and Figure 4. In order to compare the model output to that of the magnetotail as measured by the *AE* index, we plot the output of the model using vB_S as an input signal in Figure 6c. The vB_S in this case is normalized similarly to the colored noise used in the analyses of Figure 4. The regression analysis shows the slope −0.9 for the low frequencies, except for the very low ones. The slope for the high-frequency part of the spectrum is -1.9 [*Takalo et al.*, 1999b] with a break point in the slope close to that in Fig. 4.

4. Probability-Density Distribution Functions

Takalo et al. [1999a, 199b] have shown earlier that the coupled-map model has a power law distribution for duration and size of the avalanches, for both a constant input [*Takalo et al.*, 1999a] and the vB_S input [*Takalo et al.*, 1999b]. In the case of a

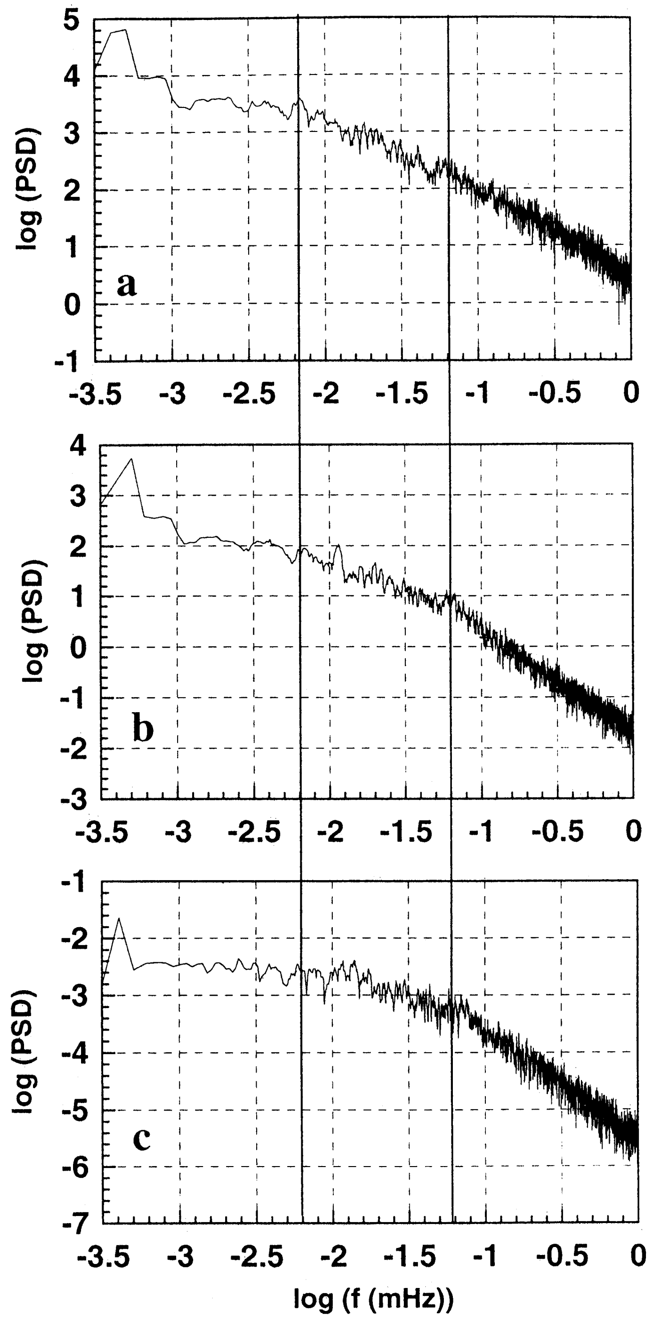

Figure 6. (a) The power spectrum of the vB_S time series from the beginning of 1979, as calculated from 32,768 points of 5-min-averaged data. (b) The power spectrum of the *AE* time series for the same period as Figure 6a. (c) The power spectrum of the model output (number of unstable sites) when vB_S is used as the input to the model. The PS is calculated similarly to that of Figure 6a.

weak constant input, *Takalo et al.* [1999a] argued that these distributions are a consequence of the self-organized critical behavior of the system. However, in the case of vB_S input [*Takalo et al.*, 1999b], the model was fed much more strongly, and it behaved more like a driven input-output system. In this case the distributions may be influenced by the dynamics of the driving. In Figure 7 we show this kind of probability-density distribution function (PDF) for the durations of the CML model when using vB_S as an input time series. As seen earlier in Figure 1, the *AE* index has a very similar distribution of durations. However, on the basis of these examples alone, it is not clear whether this scale-free property of this magnetospheric index is an intrinsic property of the magnetosphere or, at least partly, due to the driver being a scale-free time series.

Indeed, recently *Freeman et al.* [2000] have shown that the burst-lifetime distribution of vB_S and the ε function *[Perreault and Akasofu*, 1978] are of a power law form. Independently, *Takalo et al.* [2000] have shown that the polarity changes of IMF magnetic components also have power law distributions. In particular, the southward polarity of the B_Z component of IMF (B_S) plays an important role in the behavior of the magnetosphere because it enhances reconnection and thereby increases loading of energy and particles into the magnetotail. Thus the power law distribution of the southward turnings causes the power law distribution of unloadings inside the magnetotail.

The reason for the scale-free property of IMF B_Z is not clear yet, but as mentioned before, this kind of invariance is a basic property of many physical processes. As an example, we deal with the correlated (colored) noise. Furthermore, the basic property of colored noise is that its structure function

$$S(\lambda) = \left\langle \left| x(t_i + \lambda \Delta t) - x(t_i) \right| \right\rangle \tag{4}$$

scales like λ^H with H being a scaling exponent. Here Δt is sampling time, λ is an integer step, and brackets denote the average of absolute values. If this is true (at least for small values of λ), the time series is called self-affine. Furthermore, self-affinity implies that there is no preferred scale in the dynamics of the time series. The scaling exponent is related to the spectral exponent by $\alpha = 2H + 1$. Because of the condition $0 < H < 1$, the previous equation is valid only for $1 < \alpha < 3$ [*Osborne and Provenzale*, 1989; *Takalo et al.*, 1994].

To show the scale-free property of colored noise, we plot the distibution of durations for polarity changes (sign-time distribution [*Toroczkai et al.*, 1999] of 200,000 points of colored noise, with $\alpha = 1$ and 1.5, in Figures 8a and 8b, respectively. The insets show part of the time series used for the analyses. The slopes for the regression lines are -2.1 for the f^{-1} noise and -1.6 for the $f^{-1.5}$ noise. (This slope is known as the persistence exponent in the surface roughness problem [*Krug et al.*, 1997].) The reason for the smaller absolute value of the slope for the more correlated $f^{-1.5}$ noise is that the (auto)correlation makes zero crossings (sign change) of the time series less recurrent. Thus the persistence of polarity is more common for the strongly correlated time series. Actually, the slope of the distribution curve depends upon the spectral exponent of the time series such that increasing spectral exponent decreases the absolute value of the slope [*Krug et al.*, 1997]. It should be noted, however, that colored noise in nature usually has a limited band with constant spectral exponent, and usually, the absolute value of the slope, and, consequently, correlation, decreases at low frequencies. This is also the case for the IMF B_Z and *AE*. The loss of correlation at low frequencies increases the number of zero crossings (B_Z) or returnings near zero (*AE*) of the time series and consequently changes the power law slope of the distribution function. For example, for bicolored noise with spectral exponent $\alpha = 1$ for low frequencies and 2 for high frequencies, the slope of the polarity distribution is -1.4. Notice that this is similar to the slope of durations for the *AE* data and smaller in absolute value than neither of the slopes for f^{-1} or $f^{-1.5}$ colored noise.

5. Conclusions

We have shown that the CML model of magnetotail current sheet acts like a low-pass filter when driven with different types of colored noise. The dynamics related to the high-frequency part of the power spectrum is due to separate disturbances (avalanches) in the model. The slope of this high-frequency regime is almost the same independently of the color of the input time series. However, at low frequencies the power spectrum of the output time series is very similar to that of the input time series.

The power spectra of the vB_S and *AE* data (for the first half of the year 1979) resemble those of the input and output time series

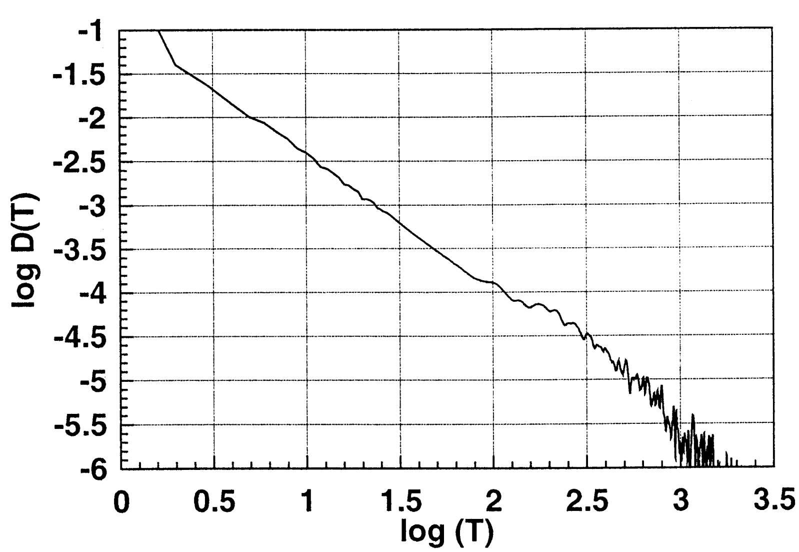

Figure 7. Distribution of the durations of 200,000 avalanches of the coupled-map lattice magnetotail field model.

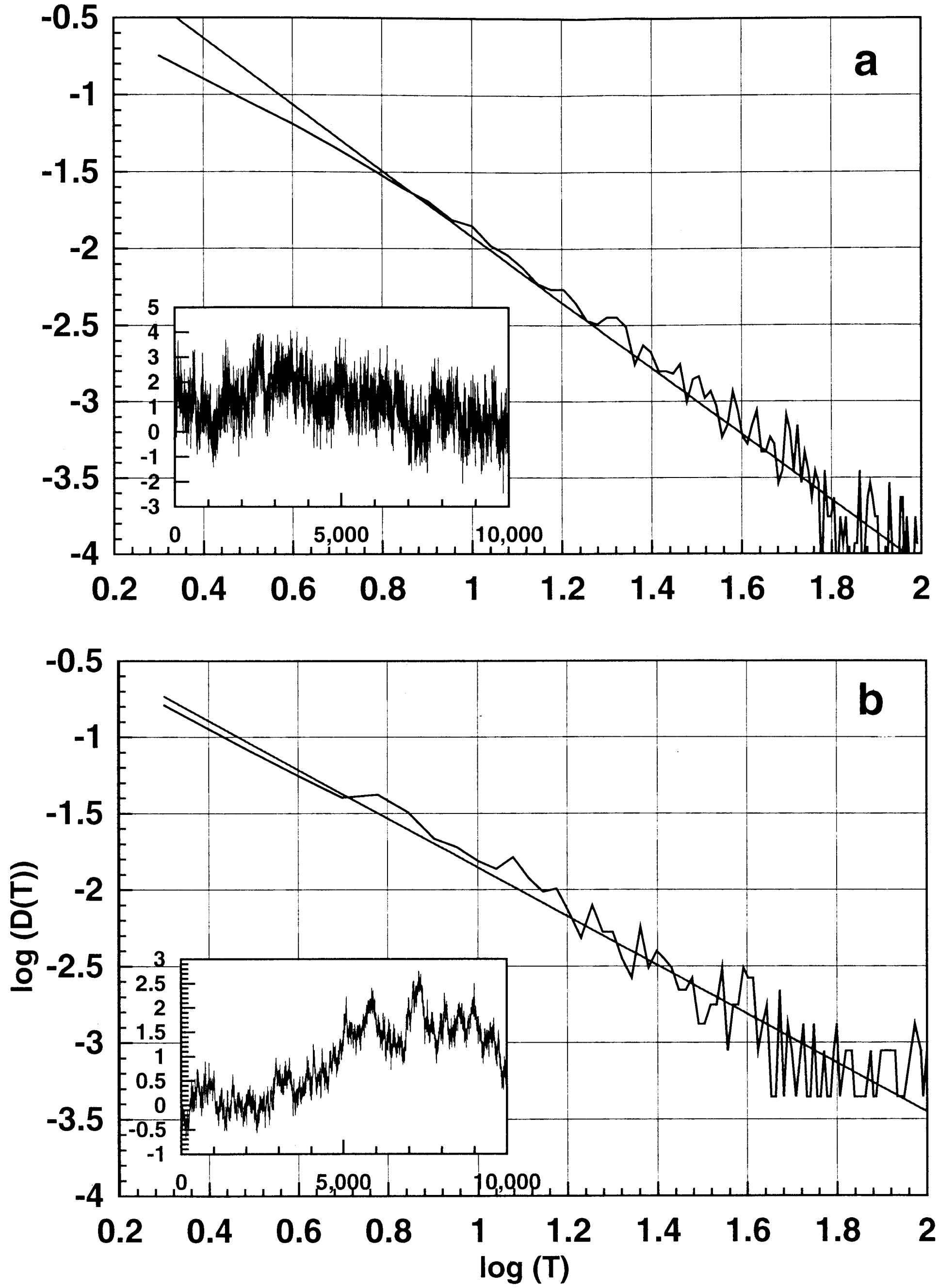

Figure 8. (a) Distribution of the polarity changes for 200,000 points of the f^{-1} colored noise. The inset shows part of the time series used for the analysis. (b) Distribution of the polarity changes for 200,000 points of the $f^{-1.5}$ colored noise. The inset shows part of the time series used for the analysis.

of the CML model, respectively. This is confirmed by the output of the model, which is similar to that of the *AE*, when vB_S is used as an input. We can thus deduce that the high-frequency part of the *AE* data is produced by the intrinsic dynamics of the magnetosphere, probably in the loading-unloading processes of the magnetotail. The origin of these disturbances may be connected to the local reconnection sites in the plasma sheet. Also, we suggest that the timescale of about 2-2.5 hours, which is seen as the break point in the power spectrum of the *AE* index at 1 per 5 hours, is the timescale of typical substorms. This timescale is seen very clearly in the westward electrojet *AL* index recorded near the local midnight (DP1 electrojet) [*Takalo and Timonen*, 1998]. On the contrary, the low frequencies of the *AE* time series closely resemble those for the IMF vB_S and probably represent the driven component of the electrojet mostly observed in the dawn and evening sectors of the auroral region (DP2 electrojet). However, the dynamics of DP1 in the midnight region is dominating the behavior of the *AE* index at high frequencies.

We also suggest that the power law distribution of the duration and size of disturbances seen in the *AE* index could be at least partly due to the corresponding power law behavior in the IMF/solar wind data [*Freeman et al.*, 2000, *Takalo et al.*, 2000]. In particular, the power law distribution of polarity changes in the IMF B_Z component means that the distribution of loading of solar wind energy to the magnetosphere has a power law form. We have shown that colored noise also has a scale-free behavior in polarity changes [*Takalo et al.*, 2000]. This is because colored noise is known to be self-affine with no preferred scale in its dynamics. The resemblance of the power spectrum of IMF B_Z to the colored noise could be one reason for its scale-free property.

However, physical systems that exhibit hierarchical coherent structures should also show phase correlation in their time series analysis. This is not the case for colored noise, which by definition has random phase distribution (see equation (3)). We have conducted phase distribution analyses for both the input and output time series of this study. However, we do not find any phase correlation or phase locking in any of these time series, neither in input nor output data. In addition, *Takalo* [1994] has shown that even a small amount of noise can diminish the phase correlation in the time series. According to his study, 5% of "pink" f^{-1} noise and only 1% of white f^0 noise could destroy the phase locking in the data of the Lorenz attractor. While the input and output data of our model may be quite noisy, these analyses cannot be conclusive in this respect, and other methods shall also be needed to determine the exact nature of the dynamics of our model and the magnetosphere.

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