Magnetospheric Dynamics from a Low Dimensional Nonlinear Dynamics Model

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Abstract

A physics based model for the coupled solar WIND–Magnetosphere–Ionosphere system (WINDMI) is described. The model is based on truncated descriptions of the collisionless microscopic energy transfer processes occurring in the quasineutral layer, and includes a thermal flux limit neglected in the Magnetohydrodynamic (MHD) closure of the moment equations. All dynamically relevant parameters of the model can be computed analytically. The system is both Kirchhoffian and Hamiltonian, ensuring that the power input from the solar wind is divided into physically realizable energy subcomponents, a property not shared by data–based filters. The model provides a consistent mathematical formalism in which different models of the solar wind driver, ionospheric dissipation, global field configuration, and substorm trigger mechanism can be inserted, and the coupling between the different parts of the system investigated.

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I. INTRODUCTION

The two standard descriptions of the magnetospheric system are (i) that of a driven magnetosphere with the causal, time delayed, direct, presumably nonlinear, response to the solar wind Interplanetary Magnetic Field (IMF) input and (ii) that of the storage, triggering and rapid (explosive) release of energy stored in geomagnetic plasma. The second description is almost exclusively based on a scenario for the bifurcation of a large volume of reversed magnetic field energy in the geomagnetic tail produced by some form of the tearing mode perturbation that reconnects magnetic field lines. In such a reconnection perturbation $\boldsymbol{\xi}_{RC}(\boldsymbol{x})$ the plasma sheet is locally pinched with the result that the laminar reversed magnetic field configuration bifurcates into a pair of X–O –points. The plasma trapped around the O–point forms a plasmoid that is ejected tailward, and the plasma at the X– point forms a region of strong local heating and acceleration of mass flow parallel to the magnetic field. This scenario, based on the formation of an X–line in region $X = -10$ to $-20\,R_E$, is called the near–earth neutral line (NENL) model of substorms and has been so extensively developed by theorists and modelers that it has become a paradigm for correlating a variety of different particle, electric, and magnetic measurements taken during times of enhanced geomagnetic activity. As clearly pointed out by the Alaskan group [1,2] the NENL paradigm has yet to prove itself as a real physical model of substorm activity. The recent view of the issue has been a compromise, with both the directly driven response and the storage–unloading mechanism retained [3]. The model presented here belongs to this category having both features.

At the present time the best predictive models of substorm activity are input–output methods based on signal processing techniques that use linear and nonlinear filters with weights determined from the database. In the past few years there has been rapid development of purely empirical modeling methods using causality, and in some cases linearity, of the magnetospheric response to the solar wind input (e.g. [4,5]). Other more complex predictive techniques include state space reconstruction procedures (e.g. [6–8]) and neural networks [9,10]. These methods are based on modern developments in time series analysis and the use of trained or "intelligent" networks to provide forecasting capabilities without setting up a particular physical model.

Input–output methods use filters to map input time series into predictions for a measure of the geomagnetic activity, usually the minute–timescale AL index and the hour–timescale Dst index. They rely on having an adequately sampled state space, and use various linear and nonlinear methods to interpolate between the data points (with either global or local interpolation coefficients). They perform well as predictors, but are difficult to interpret physically. Physics based models can offer insight into the processes involved, but are more difficult to develop than filters. Physics based models can also be viewed as input–output filters whose 'interpolation' algorithms are determined by the physics included in the model. The (as yet untested) promise of physics based models is that by including our physical understanding of the system their 'interpolation' schemes will be more powerful than the ad–hoc interpolation schemes of signal filters, and will therefore perform better in sparsely sampled areas of state space and/or require less frequent recalibration as the input signal wanders through different regions of phase space (we should repeat here that this is a 'long horizon' conjecture, which can be tested only after a physics based model is well developed and understood). A new method of deriving analogue models from magnetospheric databases has also been developed by [11]. The method promises to bridge the gap between purely forecasting data based filters and physics based dynamical models by deriving systems of ordinary differential equations (ODEs) that track the data as well a prediction filters, but are easier to interpret physically.

WINDMI is a physics based model for the coupled solar WIND–Magnetosphere–Ionosphere system [12,13]. The model is based on truncated descriptions of the collisionless microscopic energy transfer processes occurring in the quasineutral layer, and includes a thermal flux limit neglected in the magnetohydrodynamic (MHD) closure of the moment equations. All dynamically relevant parameters of the model can be computed analytically. The system is Kirchhoffian and Hamiltonian, ensuring that the power input from the solar wind is divided into physically realizable energy subcomponents, a property not shared by data–based filters.

The model provides a consistent mathematical formalism in which different models of the solar wind driver, ionospheric dissipation, global field configuration, and substorm trigger mechanism can be inserted, and the coupling between the different parts of the system investigated. So far we have carried out three such investigations:

1) Ionospheric dissipation: Using the Bargatze dataset, we obtain better agreement with the data if we use a nonlinear ionospheric dissipation that depends on the power deposited by the region–1 currents.

2) Trigger mechanism: Using the McPherron dataset, we obtain better agreement with the data if we use plasma parameters (eg. density and temperature distribution) provided by a reconnection mode particle simulation.

3) Large–scale field structure: Using the January 14–15, 1988 magnetic cloud event, we find that the model produces the correct timescales for the interaction between the magnetosphere and ionosphere [14].

In the next section we will give a brief description of the model features that are most pertinent to this study. In Sec. III we will describe new results on the ionospheric conductivity and trigger mechanism.

II. DESCRIPTION OF THE MODEL

WINDMI is a physics based model for the coupled Solar Wind–Magnetosphere–Ionosphere system [12,13]. It couples the four basic energy components of the nightside magnetosphere

1. Magnetic field energy: $$W_B = \int \frac{B^2}{2\mu_0}\, d^3x = \frac{1}{2}\,\mathcal{L}I^2 + \frac{1}{2}\mathcal{L}_I I_1^2 - MII_1 \qquad (1)$$

2. $\boldsymbol{E} \times \boldsymbol{B}$ kinetic energy: $\quad K_\perp = \int \frac{1}{2}\,\rho_m u_E^2 d^3x = \frac{1}{2}\,CV^2 + \frac{1}{2} C_I V_I^2$

$$\tag{2}$$

3. Parallel kinetic energy: $\quad K_\parallel = \int_{\text{CPS+PSBL}} \frac{1}{2}\,\rho_m u_\parallel^2 d^3x \quad (3)$

4. Thermal energy: $\quad U = \int_{\text{CPS}} \left(P_\perp + \frac{1}{2}\,P_\parallel\right) d^3x \cong \frac{3}{2}\,P_0\Omega \quad (4)$

to the ionosphere via the region 1 currents. Equations 1 and 2 serve as the definitions of the inductances and capacitances associated with current loops and electric potentials. The model is a 6–dimensional 13–parameter system, given by:

$$\mathcal{L}\,\frac{dI}{dt} = V_{\text{sw}}(t) - V + M\,\frac{dI_1}{dt} \tag{5}$$
$$C\,\frac{dV}{dt} = I - I_1 - I_{ps} - \Sigma V \tag{6}$$
$$\frac{3}{2}\,\frac{dP}{dt} = \Sigma\,\frac{V^2}{\Omega} - u_0\,K_\parallel^{1/2}\Theta(I - I_c)P \tag{7}$$
$$\frac{dK_\parallel}{dt} = I_{ps}V - \frac{K_\parallel}{\tau_\parallel} \tag{8}$$
$$\mathcal{L}_I\,\frac{dI_1}{dt} = V - V_I + M\,\frac{dI}{dt} \tag{9}$$
$$C_I\,\frac{dV_I}{dt} = I_1 - \Sigma_I V_I \tag{10}$$

The quantities $\mathcal{L}$, C, Σ, $\mathcal{L}_I$, C_I, and Σ_I are the magnetospheric and ionospheric inductance, capacitance, and conductance respectively. The currents and linked magnetic fluxes are shown in Fig. 1. M is the mutual inductance. The pressure gradient driven current is given by $I_{ps}(t) = \alpha P^{1/2}(t)$ as derived from $\boldsymbol{j} \times \boldsymbol{B} = \nabla P$ force balance and Ampére's law. The parameter α is an average over the pressure profile in the current sheet. The solar wind driving voltage in Eq. (5) is given $V_{\text{sw}} = \beta_{\text{sw}} V_x^{\text{sw}} B_s^{\text{IMF}} L_y$, where β_{sw} reflects the efficiency with which the solar wind electromotive force is translated into a cross–tail potential drop (cf. [15]). The solar wind voltage $V_{\text{sw}}(t)$ is the input time series for this nonlinear driven–dissipative system. The term $u_0\,K_\parallel^{1/2}\Theta(I - I_c)P$ represents the rapid unloading of the stored energy when the current exceeds a critical value, I_c, and comes from the heat flux limit that is neglected in the MHD closure, as we will explain below. In the absence of driving ($V_{\rm sw} = 0$) and damping ($\Sigma_I = 0$), and below the unloading limit ($I < I_c$) the total energy is conserved ($d/dt[K_\perp + K_\parallel + W_B + U] = 0$).

The basic justification for truncating the full dynamics of the complex system to a low dimensional model comes from the observation that the magnetotail is a highly stressed system near a critical point [16]. The theory of reduced representations of systems near a critical or bifurcation point is called self–organized criticality. An example of such a model for a driven system is found in [17]. Here we indicate briefly the relation of the low dimensional model to the full moment equations while acknowledging that a systematic derivation from the momentum equations is not possible. A more extensive treatment can be found in [12].

The moments of the Vlasov equation for species of index a give the following equations:

$$\frac{\partial n_a}{\partial t} + \nabla \cdot (n_a \boldsymbol{u}_a) = 0 \tag{11}$$

$$m_a n_a \left(\frac{\partial}{\partial t} + \boldsymbol{u}_a \cdot \nabla \right) \boldsymbol{u}_a = n_a e_a (\boldsymbol{E} + \boldsymbol{u}_a \times \boldsymbol{B}) - \nabla P_a - \nabla \cdot \boldsymbol{\pi}_a \tag{12}$$

$$\frac{3}{2} \frac{\partial P_a}{\partial t} + \nabla \cdot \left(\boldsymbol{q}_a + \frac{5}{2} P_a \boldsymbol{u}_a + \boldsymbol{u}_a \cdot \boldsymbol{\pi}_a \right) - \boldsymbol{u}_a \cdot \nabla P_a = \boldsymbol{u}_a \cdot \nabla \cdot \boldsymbol{\pi}_a \tag{13}$$

where closure requires a specification of the thermal flux $\boldsymbol{q}_a$ in terms of $n_a, \boldsymbol{u}_a, P_a$. In the MHD closure, the simplifications are (i) neglect the divergence of the heat flux $\nabla \cdot \boldsymbol{q} = 0$, (ii) drop the off–diagonal momentum flux $\boldsymbol{\pi}_a = 0$, (iii) neglect the diamagnetic flow velocities $v_{di} = (\rho_i/L)v_i$ compared to the MHD velocity $E_\perp/B$, and (iv) neglect the electron inertia $m_e/m_i \to 0$. In the central plasma sheet the local ion gyroradius parameter $\epsilon = \rho_i \max(\partial B/B\partial x) \sim \rho_i/R_c$ becomes large and assumptions (i) through (iii) fail. The essential non–MHD physics included in the model is therefore given by:

a) The collisionless transport for the geomagnetic tail, which appears in the finite value of $\boldsymbol{u}_i \cdot \nabla \cdot \boldsymbol{\pi}_i$ that transfers energy between Eqs. (12) and (13) and provides an irreversible energization of the ions. The large ion gyroradius conductivity gives a finite conductance

Σ and nonadiabatic ion thermalization in the quasineutral sheet $\Delta Z = (\rho_i L)^{1/2}$ which vanishes in the MHD limit. The conductivity was derived from theory and test particle simulations [18,19] and contains the Lyons–Speiser [20] energization mechanism for the transient ions as part of the ensemble average over the modified Harris sheet equilibrium.

b) The kinetic loss rate of thermal energy. We model the outflow terms by $q_n \simeq P u_n = P u_\| \simeq P(2K_\|/m_i)^{1/2} \equiv u_0 P K_\|^{1/2}$, so the thermal energy loss rate is described by the parallel heat flux (the skewness of the ion velocity distribution), represented by the heat flux limit parameter u_0, and the mean parallel flow velocity associated with the MHD parallel flow kinetic energy, $K_\|(t)$. The Geotail particle data, currently being analyzed with respect to the parallel thermal flux by [21], show that the minimum ratio of the thermal plasma energy density P to the kinetic energy density $(1/2)\rho v^2$ found in the central plasma sheet is consistent with a parallel heat flux $q_\|$ taken as a fraction of $P v_\|$.

The model can be viewed as a prediction filter, a hybrid between an Autoregressive Moving Average (ARMA) filter and a Neutral Network (NN). Writing the six ODEs in finite difference form with a substantial time step shows the relation to the ARMA system, while the nonlinear switch for the unloading of the central plasma sheet pressure plays the role of the switch–on function in the NN system. In a NN the input signals are summed according to weights from the preceding layer. Here the switch is triggered by the most recent value of the geotail current or current density and uses the values of the pressure and the parallel kinetic energy to determine the response to the system going critical. Using WINDMI as a prediction filter gives us the ability to judge different models for its components (substorm trigger mechanism, ionospheric dissipation mechanism, magnetic field configuration, etc.) within a consistent mathematical formalism.

So we see that WINDMI is based on truncated descriptions of the collisionless microscopic energy transfer processes occurring in the quasineutral layer, and includes a thermal flux limit neglected in the MHD closure of the moment equations. All dynamically relevant parameters of the model can be computed analytically through their energy integral definitions [12,13]. The system is both Kirchhoffian and Hamiltonian, ensuring that the power input from the solar wind is divided into physically realizable energy subcomponents. Viewed as a prediction filter, the model provides a consistent mathematical formalism in which different models of the solar wind driver, ionospheric dissipation, global field configuration, and substorm trigger mechanism can be inserted, and the coupling between the different parts of the system investigated.

A. ionospheric dissipation

Using the Bargatze dataset, we investigated the performance of WINDMI as a prediction filter for different values of the ionospheric conductance, Σ_I. We found that a constant conductance of a few mhos for the ionospheric response results in values of the I_1–current that are too low in magnitude and too slowly varying in time to account for the AL index. Realizing that the power deposited into the ionosphere is large ($\geq 10^9$ W) we turned to using a nonlinear conductance $\Sigma(P_{\rm ion})$ that increases with the joule heating $P_{\rm ion} = I_1 V_I$ deposited by the westward electrojet current. We adopt the Robinson formula [22] for the power flux Φ_E dependence of the Pedersen conductivity which is proportional to $\Phi_E^{1/2}$, so that Σ_I in Eq. (10) is given by

$$\Sigma_I = 1.0 + 2.0 \times 10^{-4} (I_1 V_I)^{1/2} \tag{14}$$

giving the base level of 1 mho and the increase to $1 + 2(10)^{1/2} = 7.3$ mho for an ionosphere power deposition of $I_1 V_I = 10^9$ W. Using (14), we were able to fit the Bargatze dataset with an Average Relative Variance (ARV) of 0.22–0.33, depending on the interval used (cf. Fig. 2). The nonlinear increase of the conductance with $I_1 V_I$ has the effect of making a sharp increase of I_1 that brings the model into much better agreement with the AL data. The ionospheric response time, $\tau_1 = C_1/\Sigma_1$, is now a strong function of the phase and strength of the substorm.

We have also investigated the effect of precipitating electrons by modeling the enhancement of the ionospheric conductivity using the Knight [23] formulation which gives for the observed auroral ranges $j_\parallel \sim \Delta V_\parallel$. The power flux is thus $\Phi_E = j_\parallel \Delta V_\parallel \sim (\Delta V_\parallel)^2$ and so the Robinson formula [22] gives

$$\Sigma_I = \Sigma_0 + \Sigma_1 |V - V_I| \Theta(I_1 - I_1^{cr}) \tag{15}$$

since the increase in the Pedersen conductivity is proportional to $\Phi_E^{1/2}$. The value of Σ_1 is estimated at 10^{-4}, and I_1^{cr} is the critical value of the region 1 current above which precipitating electrons would be expected to modify the ionospheric conductivity.

Figure 3 shows a comparison between the response of the model and the AL index for an event in the McPherron database. A constant ionospheric conductivity is used in Fig. 3a, and the conductivity calculated with Eq. (15) is used for Fig. 3b. Although individual cases can be found where the ohmic power model (14) does better than the precipitating electron model (15), in most cases we find that Eq. (15) gives a smaller ARV when the system is simulated. Overall, both the ohmic power model, (14), and the precipitating electron model, (15), give ARV results that are qualitatively similar.

B. trigger mechanism

At present, the dominant model of substorm triggering is that during periods of southward IMF the solar wind driven dawn–to–dusk electric field E_y measured by $V_x^{\rm sw} B_s$, reduced by the reconnection efficiency $\beta_{\rm sw}$ [24], drives the geomagnetic tail plasma current until the system is sufficiently stressed to undergo an unloading event [3]. The precise location and cause of the unloading event remains unknown. The two leading candidates are the tearing of the thinned current sheet by the onset of the resistive MHD instability as seen in MHD simulations [25], or the onset of a cross–field current driven microinstability producing a current diversion [26]. There is, however, no clear statistical correlation between either of these models and observations. Thus, there are other theories that argue either that the system is purely a driven system [27] or that the trigger for the onset of the expansion phase of the substorm lies in the condition of the solar wind [28]. Lyons argues that the trigger for substorms is in the IMF orientation rather than an internal magnetospheric instability. Such an IMF trigger appears compatible with the energy release mechanism described in [29].

WINDMI is used to investigate the NENL paradigm, by combining it with reconnection mode particle simulations. The model was used as an input–output filter, and its predictive performance was compare to the Blanchard–McPherron dataset of isolated substorms [30]. Figure 4 shows the results of the reconnection mode particle simulations that are used to calculate the parameters for the run shown in Fig. 5. The density profile from the particle simulations is used to calculate the capacitance using equation 2, while the parameter α in the formula for pressure gradient driven current, $I_{ps} = \alpha\sqrt{P_0}$, is calculated by averaging over the pressure profile. We see that, when particle simulations are used to calculate the model parameters, the NENL paradigm is consistent with the data.

The value of the unloading rate, u_0, used in the results shown in Fig. 5 is obtained empirically by minimization. The next stage in the investigation of the NENL paradigm is to calculate u_0 from the contribution of the off–diagonal elements of the pressure tensor, $\boldsymbol{\pi}$, which is neglected by MHD, as given by our reconnection mode particle simulations. The importance of the off–diagonal elements of the pressure tensor in the tail force balance has been noted before [31,32], and an effort is currently under way to calculate them from satellite plasma data [33]. Since the closure scheme used to derive WINDMI includes a finite $\boldsymbol{\pi}$, the model is well suited to investigate the tensor's contribution to momentum balance in the quasineutral layer. Figure 6 shows the same run as Fig. 5, but with u_0 given by the particle simulations, instead of a value obtained from minimization. We see that, although not optimal, agreement is still quite good.

III. SUMMARY

WINDMI is a nonlinear dynamical model for the coupled solar wind–Magnetosphere–Ionosphere system [12,13]. The model is based on truncated descriptions of the collisionless microscopic energy transfer processes occurring in the quasineutral layer, and includes a thermal flux limit neglected in the MHD closure of the moment equations. All dynamically relevant parameters of the model can be computed analytically. The system is both Kirchhoffian and Hamiltonian, ensuring that the power input from the solar wind is divided into physically realizable energy subcomponents, a property not shared by data–based filters.

The model provides a consistent mathematical formalism in which different models of the solar wind driver, ionospheric dissipation, global field configuration, and substorm trigger mechanism can be inserted, and the coupling between the different parts of the system investigated. So far we have carried out three such investigations:

1) Ionospheric dissipation: Using the Bargatze dataset, we obtain better agreement with the data if we use a nonlinear ionospheric dissipation that depends on the power deposited by the region–1 currents [13]. For the power flux Φ_E from precipitating electrons in the Robinson conductivity we used two models. The simplest model, is to take this energy flux proportional to the ohmic power. The second model, which seems to give the best performance, is to use the standard current–voltage relationship with the Lyons–Evans conductance parameter, and include an ionospheric current trigger for $I_1 > I_1^{cr}$.

2) Trigger mechanism: Using the McPherron dataset, we obtain better agreement with the data if we use plasma parameters (e.g. density and temperature distribution) provided by a reconnection mode particle simulation [30]. We find that the contribution of the heat flux to the energy unloading is also important. When particle simulations are used to obtain the value of the unloading parameter, u_0, agreement with data is also good.

3) Large–scale field structure: Using the January 14–15, 1988 magnetic cloud event, and modeling the field with the Tsyganenko 96 model, we recover the observed timescales for the coupling of energy between the ionosphere and the magnetosphere (see [14]).

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